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Summary

The analysis, dynamic simulation, and design optimization of the short spacer truss of the Space Station Freedom are presented in this report. The short spacer truss will be positioned between the integrated equipment assembly (IEA) and another truss, called the long spacer truss, in the Space Station Freedom. During its launch in the Space Shuttle, the truss will be subjected to considerable in-span distributed inertia loads due to shuttle accelerations. The short spacer truss, therefore, has been modeled as a space frame to account for flexural response. Several parameters have been assumed, since the design specifications are in the process of development; hence the results presented should be considered preliminary. However, the automated analysis and design capabilities that have been developed can readily be used to generate an optimum design of the short spacer truss once the actual specifications have been determined.

This report includes (1) static and dynamic analyses of the short spacer truss, which have been obtained with the linear elastic code LE_HOST (in these analyses, LE_HOST data files have been automated to facilitate their future use for different design specifications of the short spacer truss); (2) the dynamic animation of the short spacer truss, which has been carried out by using the results of the dynamic analysis and a post-processing feature of the modeling code PATRAN; and (3) the optimum-weight design of the spacer truss, which was obtained under prescribed stress, displacement, and frequency constraints by using the design code COMETBOARDS.

Examination of the analysis and design results revealed that the design could be improved if the configuration of the short spacer truss were modified to a certain extent. A modified configuration, which may simplify fabrication, has been suggested. The performance of this configuration has been evaluated and was found to be satisfactory under both static and dynamic conditions.

Introduction

The Space Station Freedom is to be built on a low-Earth orbit (at an altitude of 208 mi) from components and subsystems launched onto such orbit through multiple Space Shuttle missions. A preliminary configuration of the Freedom station (which covers an area of about 2 acres) is depicted in figure 1. The main structure of Freedom can be considered, in essence, to be a long, trussed beam with several cantilevered appendages that support photovoltaic power modules, thermal control radiators, microgravity laboratories, habitation modules, and such (see fig. 1). Freedom will be powered by photovoltaic modules located on its starboard and port sides. The starboard photovoltaic (PV) power module consists of two solar array blankets positioned 590 in. apart. To maintain the distance between the PV assemblies and to also comply with the launch dimensions of the cargo bay of the Space Transportation System (STS), two trusses, termed the "short spacer truss" and the "long spacer truss," will be provided.

The objective of this report is to describe a capability for automated static and dynamic analyses, along with animation and design optimization, of the short spacer truss under landing load conditions. Since the design specifications and the configuration of the spacer truss are still being generated, results provided here should be considered preliminary. These results are presented only to demonstrate the design capability developed. However, once the actual design specifications are available, the present capability can readily be used to analyze and design a truss that may be a candidate to fly on the Space Station Freedom. Static and dynamic analyses of the short spacer truss were carried out with the linear elastic code LE_HOST of the structural analysis code MHOST (ref. 1). The PATRAN (ref. 2) post-processing capability was augmented with the dynamic analysis results to generate a dynamic animation of the short spacer truss model.

The design optimization of the short spacer truss was cast as a constrained nonlinear mathematical programming problem, and it was solved by using the COMETBOARDS code (ref. 3). COMETBOARDS is an acronym for Comparative Evaluation Test Bed of Optimizers and Analyzers for the Design of Structures; it is being developed in the Structural Mechanics Branch of the Structures Division at the NASA Lewis Research Center. The COMETBOARDS code is an appropriate tool for design optimization of Freedom station components since it can handle both static and dynamic constraints, thereby ensuring a safe launch in the STS and a satisfactory performance in the hostile space environment of orbit. In brief, the LE_HOST code was used to analyze the short spacer truss in static and dynamic regimes, including dynamic animation, whereas the COMETBOARDS version 1.0 was used to optimally design the short spacer truss for minimum mass under constraints of strength, displacement, and frequency.

Overall examination of the results revealed that certain changes to the configuration of the short spacer truss could enhance the design. Therefore, we suggest a modified configuration of the

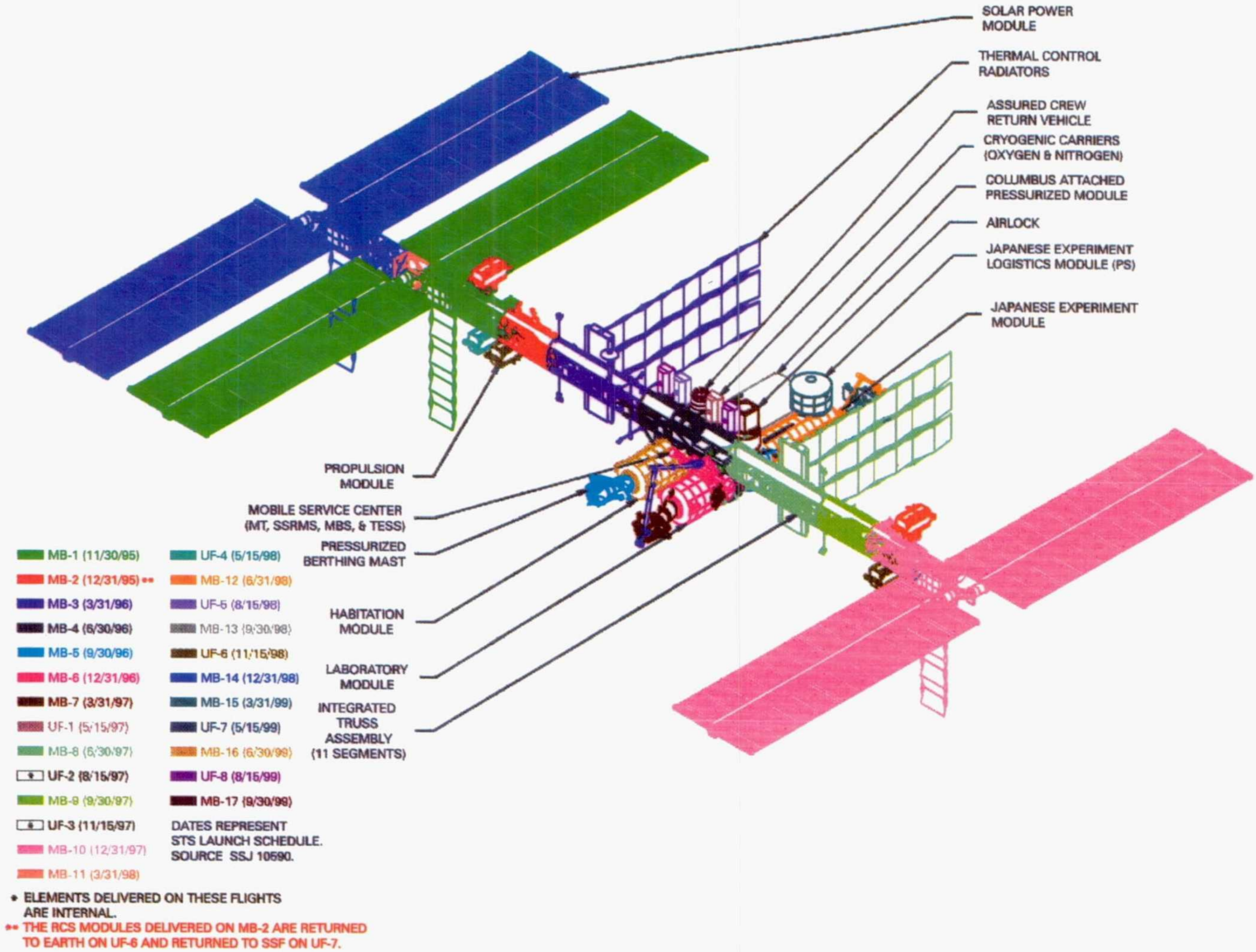


Figure 1. – Assembly sequence overview of Space Station Freedom (fig. courtesy of Boeing).

short spacer truss whose performance has been assessed under static as well as dynamic conditions.

The subject matter of this report is presented in six sections: Preliminary Configuration of the Short Spacer Truss; Design Specifications; Finite Element Analysis; Design Optimization; Design Suggestions; and Conclusions.

Preliminary Configuration of the Short Spacer Truss

The preliminary configuration of the short spacer truss, which is depicted in figure 2, has 14 joints and 41 members. The truss is 135.5 in. long, 101.5 in. wide, and 77.9 in. deep. The members are made of tubular aluminum; an outer diameter of 2.5 in. and a thickness of 0.2 in. are being considered as initial dimensions of the annuler cross section (ref. 4). During its launch in the STS, the truss is to be supported in the cargo bay at three points (also referred to as the three-point launch support). Two support points are provided by the two longeron trunnions, and the other one by

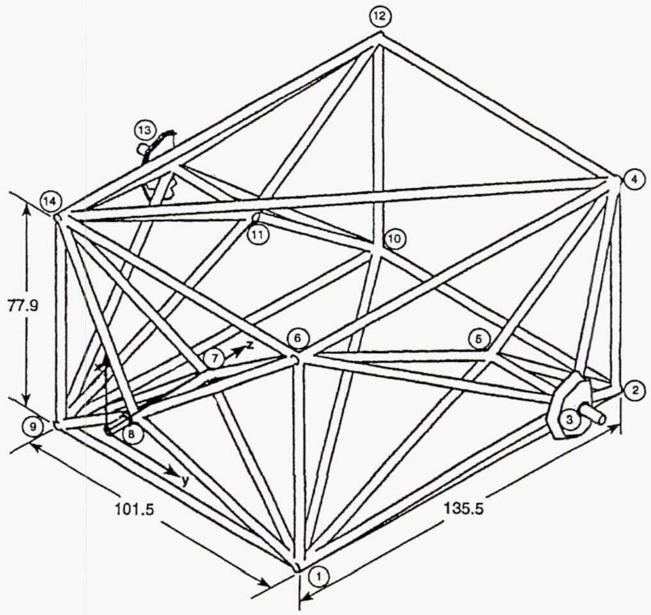
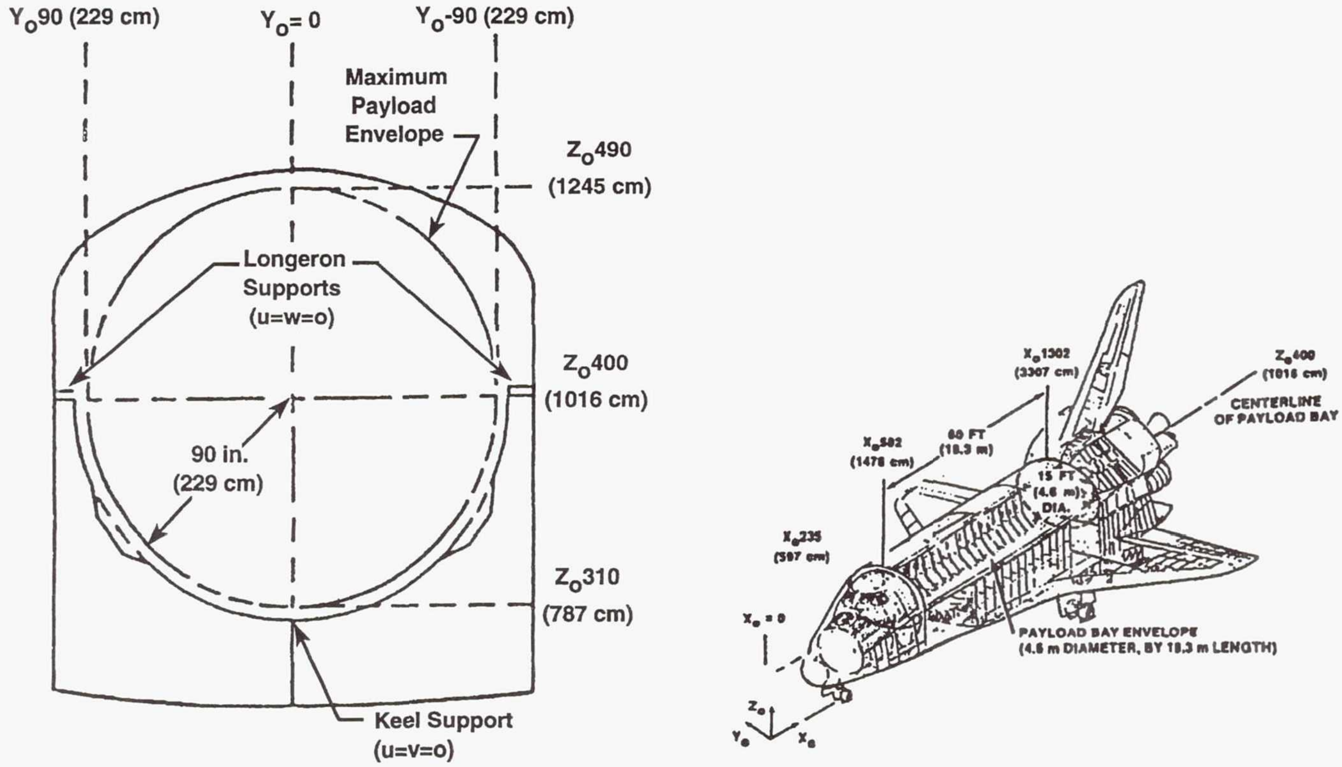


Figure 2. – Preliminary configuration of short spacer truss (all dimensions are in inches).



(a) Mid-fuselage view looking aft.

(b) Space Transportation System.

Figure 3.—Support locations in Space Transportation System.

the keel trunnion, as shown in figure 3. At each of these supports the trunnions can expand along their axes, whereas the other two translational degrees of freedom are prevented; that is, the displacements in both the x- and z-directions at the longeron trunnions and the displacements along the x- and y-axes at the keel trunnion are restrained. The trunnions are solid tubes; the longeron tubes are 3.244 in. in diameter and the keel tube is 2.996 in. in diameter. All truss members are made of 6061–T6 aluminum, whereas both the longeron and keel trunnions (ref. 5) are made of Inconel 718. The properties of both materials are given in table I.

TABLE I.—PROPERTIES OF THE SHORT SPACER TRUSS MATERIALS

Material	Young's modulus, psi	Poisson's ratio	Density, lb-sec^2/in.^{4}	Permissible stress, psi
Aluminum (members)	9.9×10^6	0.303	0.2539×10^{-3}	30 000
Inconel (trunnions)	29.4×10^6	.29	$.7694\times10^{-3}$	71 428

For dynamic analysis, both distributed element masses and concentrated nodal masses were considered. The distributed member mass was accounted for through a consistent formulation. The concentrated nodal masses simulated the connection weight, mass of the scuff plates, equipment mass, and so on (ref.5), as shown in figure 4. The pseudo static design loads for the short spacer truss, as given in Space Shuttle specifications applicable to the truss (ref.6), were generated as a combination of several launch events. However, to demonstrate the analysis

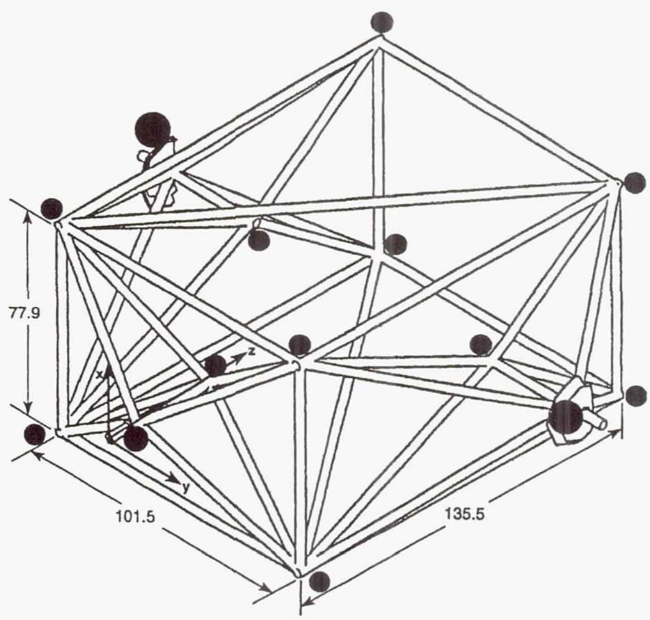


Figure 4.—Short spacer truss-joint masses (all dimensions are in inches).

and optimum design capabilities (through the analysis code LE_HOST and optimization software COMETBOARDS), only the emergency landing load was considered, because such a load condition produces a load system that most likely encompasses a number of other load events.

Design Specifications

Several assumptions were made for the analysis and design optimization of the short spacer truss:

(1) The baseline configuration of the short spacer truss would be 135.5 in. long, 101.5 in. wide, and 77.9 in. deep.

(2) The nodal masses supplied by the Space Station Freedom Directorate should be used in the dynamic analysis and animation (see fig.4 for their locations).

(3) Only an emergency landing load condition with a safety factor of 1.5 should be considered for the static analysis and design.

(4) The design shall be applicable only for a launch configuration with three-point supports. (The on-orbit configuration, along with the effect of the neighboring long spacer truss (LST), integrated equipment assembly (IEA), and such, was not considered.)

(5) The displacement limitations at the exterior joints (i.e., joint numbers 1, 2, 3, 4, 6, 8, 9, 10, 12, 13, and 14 (fig.2)), are less than 1.0 in.

(6) Fundamental frequency, which became active during design optimization, is 14 Hz. (This needs to be verified.)

(7) Material properties are as given in table I.

Once the Space Station Freedom Directorate examines the aforementioned design limitations and provides the correct design specifications and the actual configuration, we shall be able to generate the actual design of the short spacer truss. In other words, the design given here should be considered preliminary and must not be used to fabricate any flight hardware.

Finite Element Analysis

A finite element stiffness method as implemented in the analysis code LE_HOST was used to analyze the short spacer truss. Even though the structure is called a truss, the load is distributed along the member spans. Such in-span distributed loads produce considerable bending response. Therefore, for the purpose of analysis and to ensure accuracy for static and dynamic analysis, the short spacer truss was modeled as a space frame with rigid joints and a varying number of beam elements for each member.

Automatic Generation of the LE_HOST Finite Element Data File

A finite element data file for a beam element requires data such as nodal coordinates, element connectivity, direction of the principal axis of the beam cross section, inertial nodal loads (due to accelerations), and element material properties, all in a format specific to the LE_HOST software. Additional inputs such as master and slave nodes, duplicated nodes, and specific key words to perform elastic and dynamic analyses are also required. Because of their complexity and because of qualification requirements, Space Station Freedom components, in particular the short spacer truss, have to be analyzed and redesigned several times before launch. This requires that LE_HOST data files be created several times. To eliminate this cumbersome task and the resulting data errors, if any, generation of input data files for the Freedom station spacer trusses has been automated. Only a few basic inputs are needed for the automated generation of the complete input file, that is, the coordinates of the physical joints and the number of elements between such joints. The finite element data files that have been generated automatically for several models (one, two, and eight elements for each physical beam of the truss) have been verified, and the post-processor PATRAN has been used to visualize these models (see figs. 5 to 7).

Finite Element Model Selection

The LE_HOST beam model (element 98) is a two-node, linear isoparametric element. It is derived from Timoshenko beam theory (ref. 7), which takes into consideration the effects of shear deformations. Linear interpolation functions are utilized to interpolate the displacements and rotations independently. The beam model has six degrees of freedom per node. The stiffness coefficients are numerically calculated by using one integration point. The convergence of the LE_HOST beam element is examined by using a single-span beam in addition to the entire short spacer truss.

Convergence study for single-span beam.—The convergence characteristics of the Timoshenko beam element have been examined for two single-span beams with tubular cross sections. The beams were made of aluminum material identical to the short spacer truss members and were subjected to uniformly distributed static loads. The first example had simply supported boundaries, whereas the second had fixed supports. The beam span (L = 100 in.) was discretized into 2, 4, 8, 16, and 24 elements. For each finite element model, the midspan displacement, maximum stress, and fundamental frequency were obtained. The responses were normalized with respect to the analytical solutions (ref. 8) and are depicted in figure 8. Note that the beam solution for both the simply supported and the fixed boundary conditions converged with a 98-percent accuracy for an eight-element model. Since this convergence occurred for an eight-element model of both beams, such a level of discretization can be considered adequate for the short spacer truss analysis. This was verified by modeling the entire structure.

Convergence study for short spacer truss.-- Convergence for the short spacer truss under both static and dynamic conditions was considered for five different finite element models. The first model had 1 element per truss member; the second model, 2 elements per member; the third, 4 elements; the fourth, 8 ele-

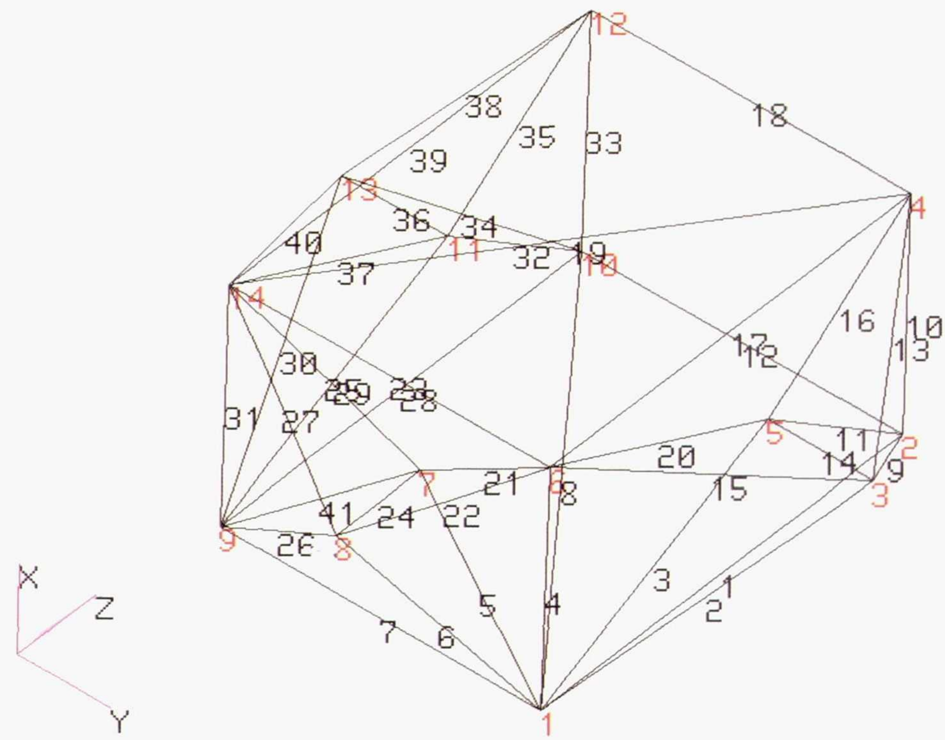


Figure 5. – One element/member finite element model.

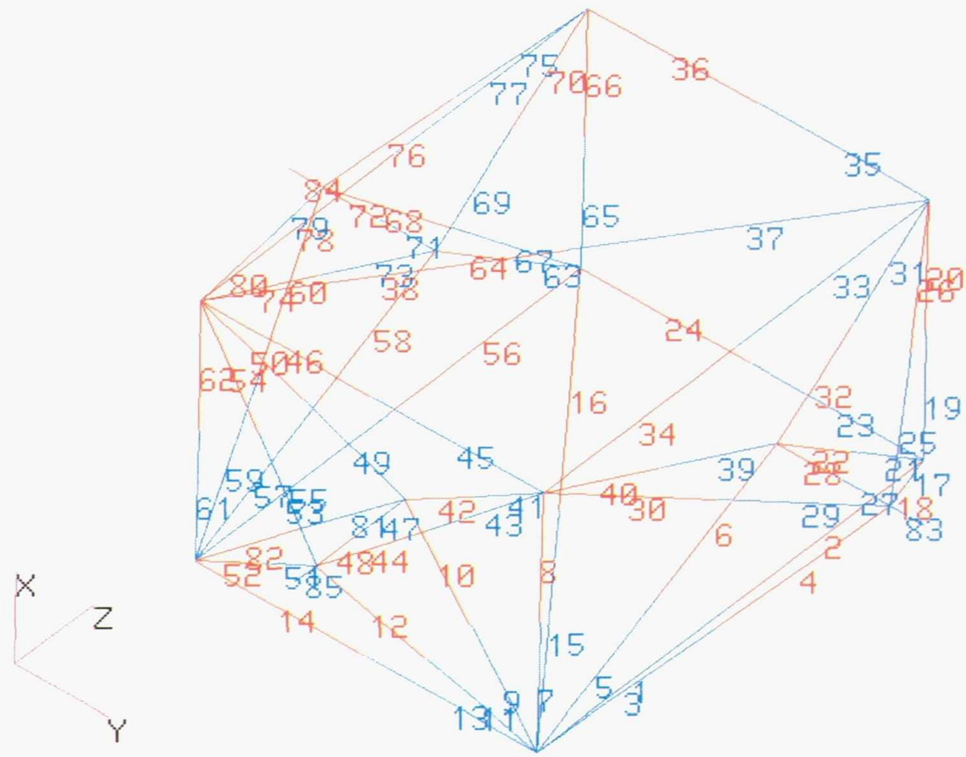


Figure 6. – Two elements/member finite element model.

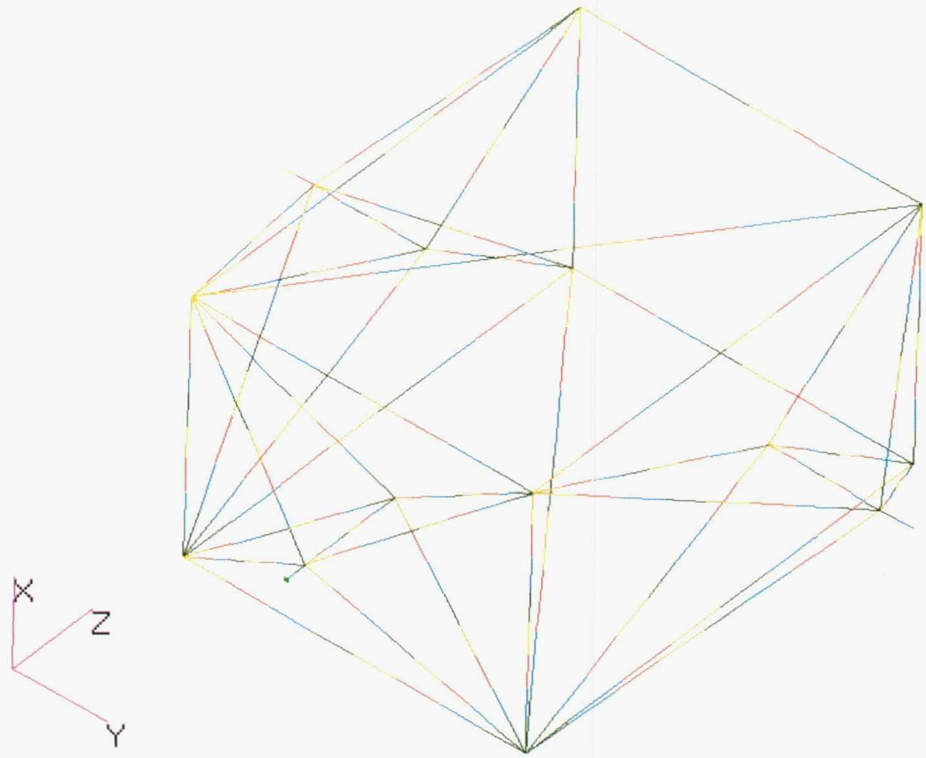


Figure 7. — Eight elements/member finite element model.

TABLE II. — CONVERGENCE RESULTS OF LE_HOST BEAM MODEL

Number of elements/ member	Number of nodes	Number of elements	Number of degrees of freedom	Frequency, Hz	Maximum displacement, in.	Maximum stress, psi
1	17	44	96	35.601	0.02355	112
2	58	85	342	16.199	.19733	10 360
4	143	170	852	15.034	.40862	13 797
8	307	334	1836	14.283	.45633	14 791
16	635	662	3804	14.169	.46915	15 465

ments; and the fifth model, 16 elements (see table II wherein the number of nodes, elements, and degrees of freedom are given for each model). These five finite element models were analyzed, and the normalized displacement, stress, and frequency are depicted in figures 9 to 11 (normalization was carried out with respect to the results of the 16-element model). The results obtained were further verified by using the MSC/NASTRAN code (ref.9) for a four-element model. Note that the MSC/NASTRAN code uses a beam element with a cubic displacement field function. Observe (figs. 9 to 11) that the solutions for the 8-element model (which has 334 elements and 1836 degrees of freedom) predict accurate results and compare well with the 16-element model (which has 3804 degrees of freedom). The eight-element model was considered to be adequate for analysis and design optimization of the short spacer truss and was selected for further investigations.

The static analysis for the eight-element model was carried out for an emergency landing load condition. The results, showing a deformed configuration and the normal stresses, are presented in figures 12 and 13, respectively. Observe that the maximum dis–placement of 0.45633 in. occurs at the middle of the diagonal

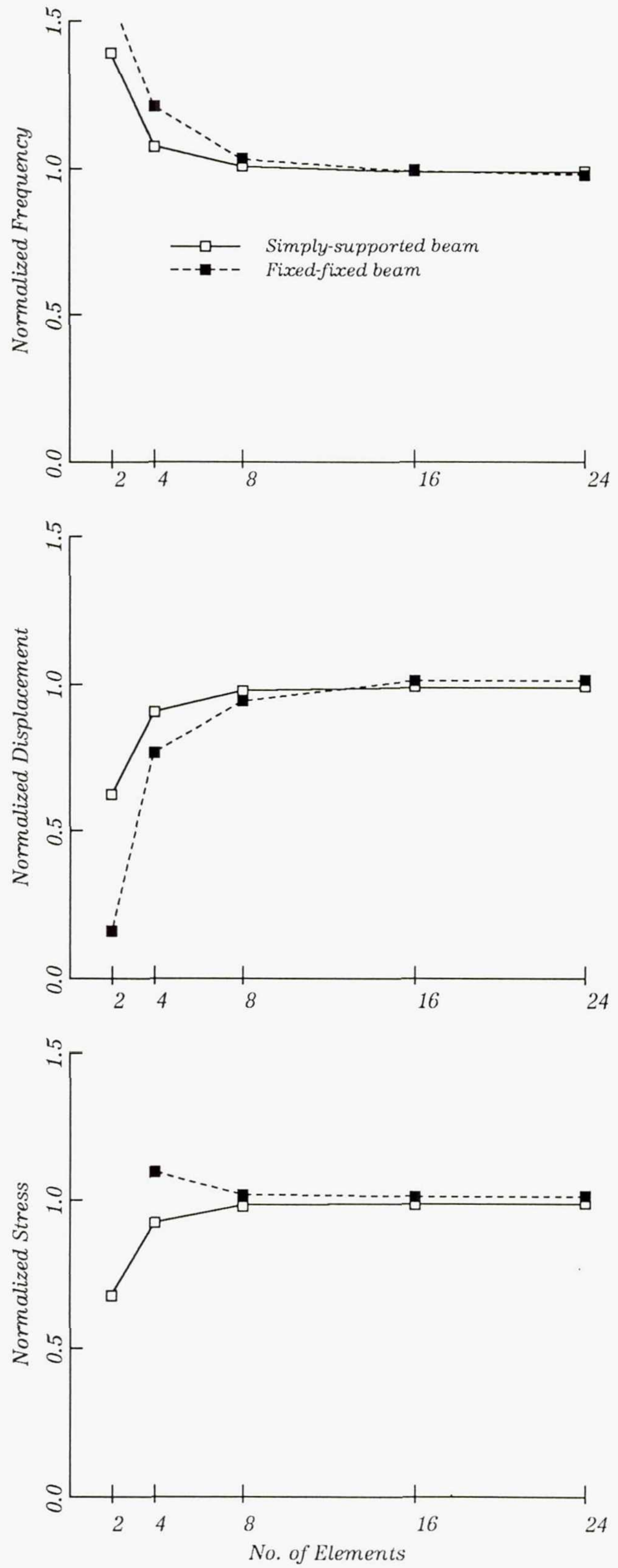


Figure 8. – Single-span beam convergence.

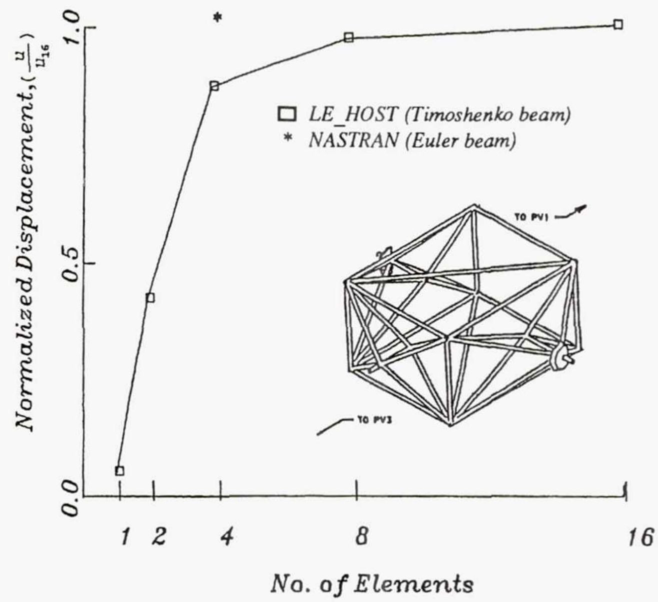


Figure 9. – Normalized frequency model validation.

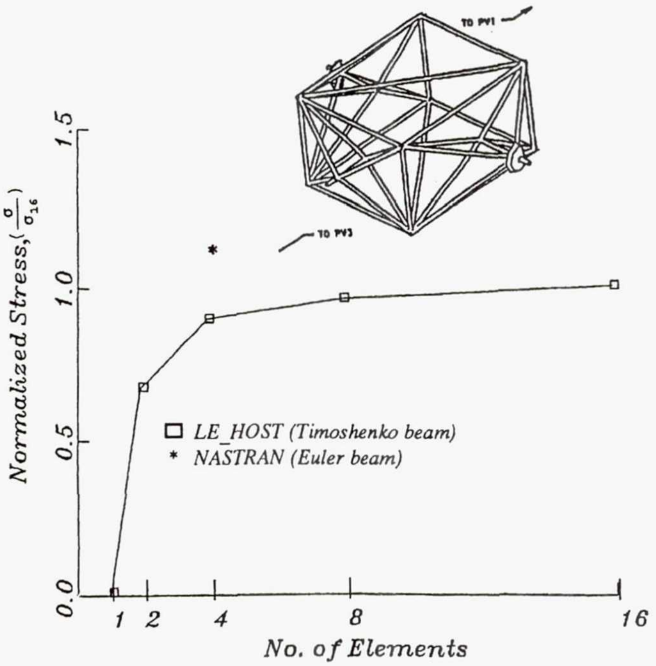


Figure 10. – Normalized displacement model validation.

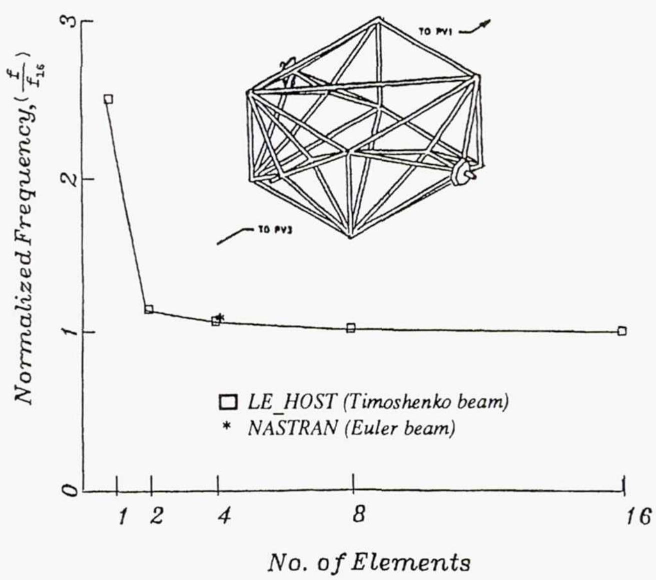


Figure 11.—Normalized stress model validation.

member (1-10) in the *y-z* plane (see figs. 2 and 12), and the maximum stress of 17 791psi occurs in member (11-13) near the support (see figs. 2 and 13).

The dynamic analysis for the eight-element model was carried out next. This model has a fundamental frequency of 14.283 Hz; the associated mode is shown in figure 14. The dynamic animation for this mode was carried out with PATRAN and was reviewed qualitatively. Deformation of the diagonal member (1-10) of the spacer truss (see fig.2) seemed to be excessive when compared to other members. The excessive deformation appeared to be due to the absence of a cross-bracing member connecting joints 2 and 9 (see fig.2). Another diagonal member, (4-14), also needs to be braced by adding a member between joints 6 and 12.

Design Optimization

The design of the short spacer truss was optimized for a minimum mass under emergency landing load conditions with stress, displacement, and frequency as the behavior constraints. Version 1.0 of the COMETBOARDS code was used to obtain the optimum design; the basic architecture of COMETBOARDS is depicted in figure 15. The code has a central command unit, Control Via Command Level Interface, which establishes links between its three primary modules, the optimizer module, the analyzer module, and the data files, to solve an optimization problem. The optimum solution then is stored in an output device.

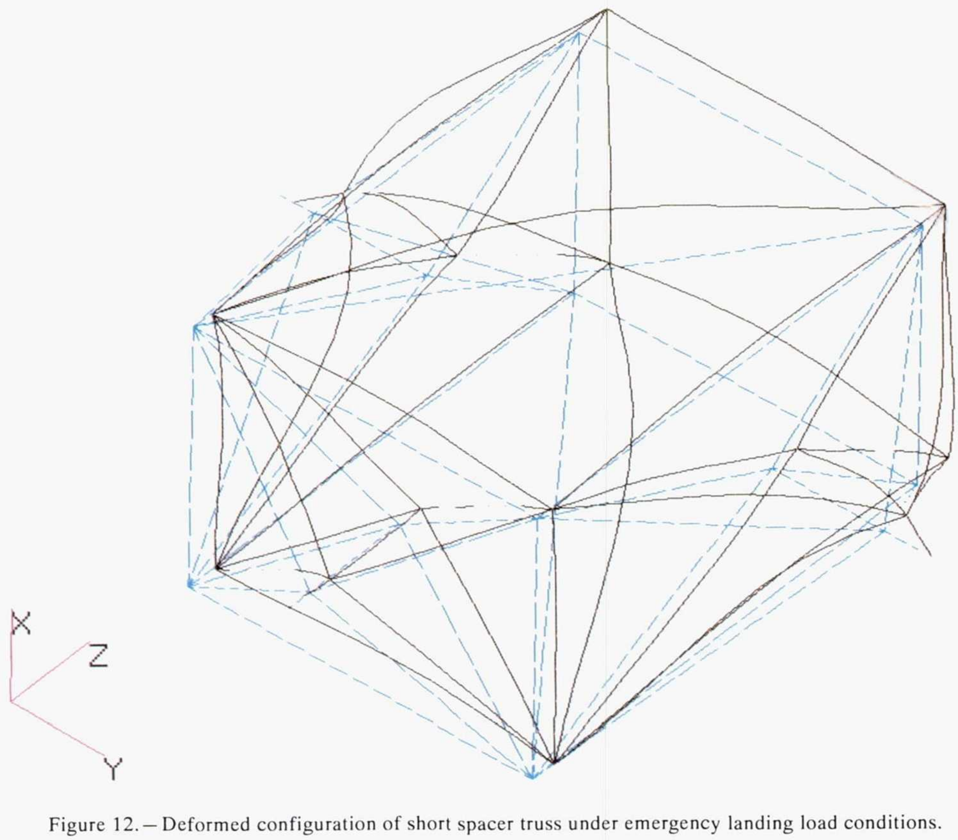


Figure 12.—Deformed configuration of short spacer truss under emergency landing load conditions.

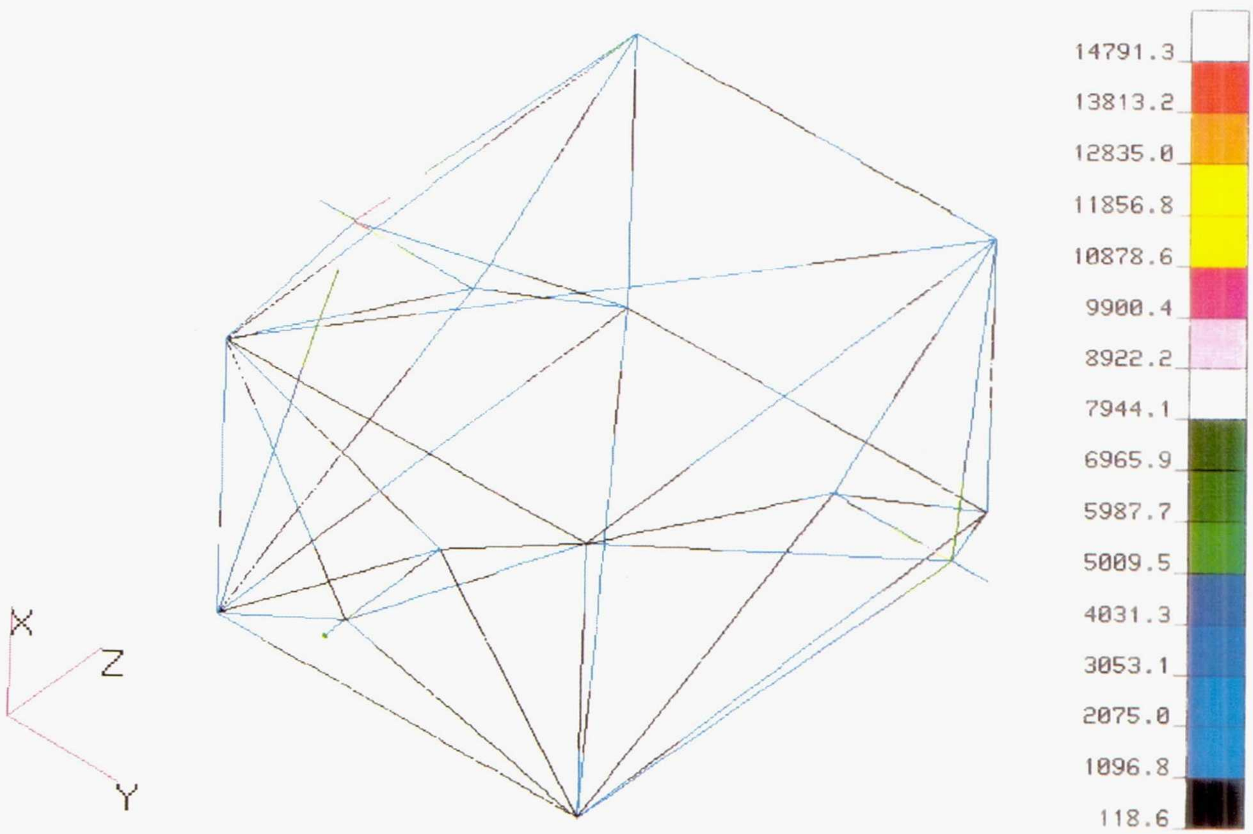


Figure 13. – Normal stress of short spacer truss under emergency landing load conditions.

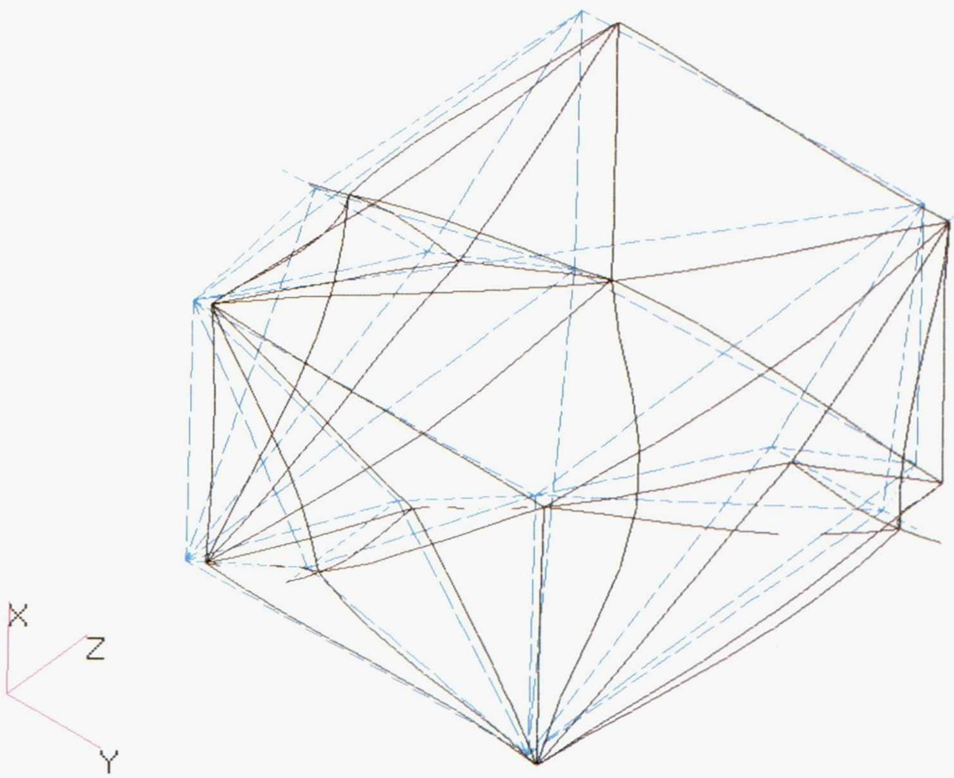


Figure 14. – First eigen mode of short spacer truss, launch configuration.

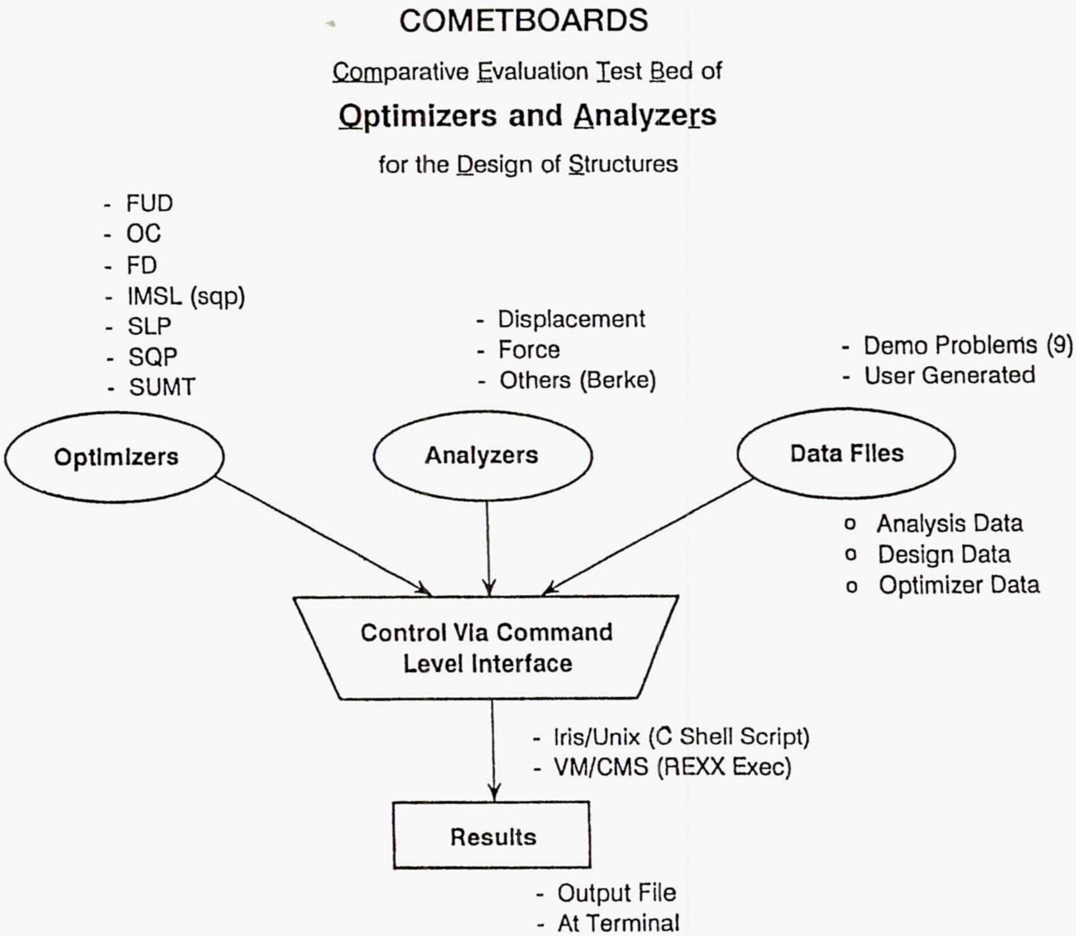


Figure 15.—Flow chart of COMETBOARDS code.

Several optimizer techniques and analyzer methods are available. Optimization techniques are the fully utilized design (ref. 10), the optimality criteria technique (ref. 11), the methods of feasible directions (ref.12), the IMSL quadratic programming method (ref.13), the sequence of linear programming (ref.14), the sequence of quadratic programming (ref.15), and the sequence of unconstrained minimization technique (ref.16). The analyzer methods are the displacement method, the integrated force method, and the simplification force method. There are three input data files: ANLDAT, for finite element analysis input; DISDAT, for data required to cast the design as a mathematical programming problem; and OPTDAT, for data that is specific to a mathematical programming technique. The latter provides convergence tolerances, stop criteria, maximum number of design iterations, and related parameters. A typical command to operate the COMETBOARDS code is given in the appendix. In brief, the COMETBOARDS code allows considerable flexibility in solving a design problem: it can choose one of several optimization techniques and one of the three analysis methods.

The design optimization of the short spacer truss has been cast as the following nonlinear mathematical programming problem:

Find the n design variables that define the areas of the truss members within prescribed upper and lower bounds and that make the scaler weight function W a minimum under a set of inequality constraints.

The weight function W of the short spacer truss can be written as

$$W = \sum_{k=1}^{m} \rho_k A_k L_k \tag{1}$$

where A_k is the cross sectional area; L_k, the length; and ρ_k, the weight density of the kth element. The frequency, displacement, and stress limitations are considered as the inequality constraints of the design problem and are specified as follows:

Frequency constraint

$$g_{fn} = \left(\frac{f_{no}}{f_n} \right)^2 - 1 \le 0 \tag{2}$$

Displacement constraint

$$g_{ui} = \left| \frac{u_i}{u_{io}} \right| - 1 \le 0 \tag{3}$$

Stress constraint

$$g_{\sigma i} = \left|\frac{\sigma_i}{\sigma_{io}}\right| - 1 \le 0 \qquad (4)$$

where f_n represents the natural frequency of the spacer truss; f_{no}, the limitation of the frequency; u_i, the ith displacement components; u_{io}, the displacement limitation for the ith displacement component; σ_i, the design stress for the ith element; and σ_{io}, the permissible stress for the ith element.

With the analysis capability of the code, COMETBOARDS version 1.0 can optimize a structure by using truss or membrane elements. Since the members of the short spacer truss behave as beams with flexural response, COMETBOARDS 1.0 can simulate the problem indirectly through a scaling technique (COMETBOARDS 2.0, which is being completed, can directly obtain the optimum design of the spacer truss by using beam elements). The truss-beam response simulation is determined by correlating the membrane and flexure behaviors through variable scaling factors for stresses, displacements, and fundamental frequency. The scaling factors are ratios between the response parameters obtained by modeling the structure both as a truss and as a beam. The beam model has eight elements for each member of the short spacer truss (see fig.7). The ratios for stresses, displacements, and frequency are given in tables III to V.

TABLE III. – STRESS RATIOS

Member number	Truss model nominal stress, psi	Beam model maximum stress, psi	Ratio
1	310.23	1 568.0	0.1977
2	−580.32	5 378.4	.1079
3	−10.38	898.6	.0116
4	−116.26	2 218.7	.0524
.	.	.	.
.	.	.	.
.	.	.	.
21	62.67	724.7	.0865
22	382.83	4 820.3	.0794
23	−181.05	986.6	.1835
24	30.16	5 732.4	.0053
.	.	.	.
.	.	.	.
.	.	.	.
38	893.78	10 352.0	.0863
39	−352.23	2 000.5	.1761
40	−313.59	3 350.7	.0936
41	196.59	1 202.7	.1635

The optimum design of the short spacer truss took into consideration 41 stress constraints (one for each member); 15 displacement constraints in the directions indicated in table IV; and 1 fundamental frequency constraint. Optimization was carried out for two cases. In the first case, all the truss members were linked to a single design variable, that is, all truss members had the same design cross sectional area. The optimum weight design was obtained by using five different optimization methods: the sequential unconstrained minimization technique (SUMT); two versions of the sequential quadratic programming algorithm, termed "IMSL" and "SQP"; the sequential linear programming technique (SLP); and the method of feasible directions (FD). Even though the rate of convergence differed for different optimizers, all the methods except the FD code converged to the same minimum weight of 386 lb, as shown in figure 16, and the optimum cross sectional area was 1.12 in.^{2} This design is 23 percent lighter than the original design. The fundamental frequency is the only active constraint of the optimum design in this case (see table VI). In the second optimization case all design variables were considered independent, that is, each member had a different cross sectional area. Optimization results obtained for this case are depicted in figure 17. As before, all the optimization methods converged to the weight of 126 lb through different rates of convergence. The optimum cross sectional areas ranged between 0.25 and 0.77 in.^{2} In addition to the fundamental frequency constraint (as in the first case), seven of the stress constraints were also active, as shown in table VII. The truss members in which the stress constraints were active are also shown in blue in figure 18. In neither case were displacement constraints active; this will ensure a safe dynamic envelop in the cargo bay during launch in the STS.

The COMETBOARDS 1.0 optimization code does not consider buckling constraints. However, COMETBOARDS 2.0 imposes both member buckling and skin crippling constraints. The COMETBOARDS 1.0 optimum design of the short spacer

TABLE IV. – DISPLACEMENT RATIOS

Joint number	Degrees of freedom	Truss model, in.	Beam model, in.	Ratio
1	1	0.00451	0.05191	0.0869
1	2	.00324	.05231	.0619
2	2	.01449	.11291	.1283
2	3	.01264	.12806	.0987
3	2	.01260	.09335	.1349
4	1	.01779	.17013	.1046
4	2	.01645	.11798	.1394
4	3	−.00197	.05427	.0363
8	3	.00943	.11633	.0811
9	3	.00733	.16294	.0449
10	1	.01949	.17000	.1146
13	2	.01539	.11222	.1371
14	1	.00653	.05501	.1186
14	2	.00486	.05506	.0882
14	3	.00246	.09828	.0249

TABLE V. – FREQUENCY RATIO

Mode number	Truss model, Hz	Beam model, Hz	Ratio
1	25.729	14.283	0.56

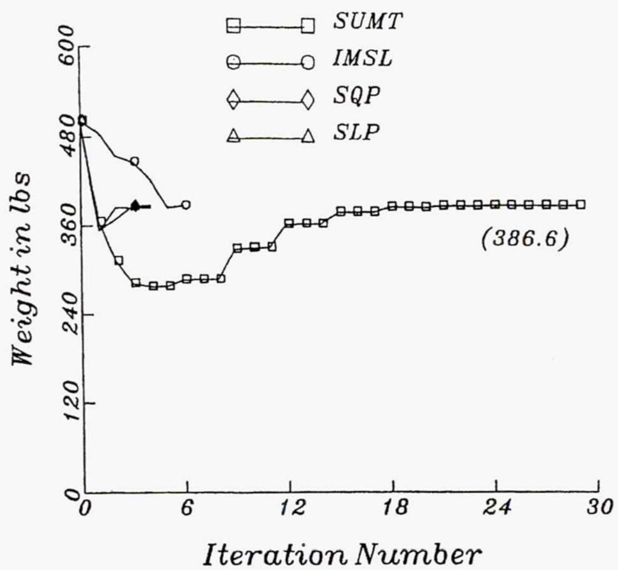


Figure 16. — Design optimization of short spacer truss with one design variable.

TABLE VI. — OPTIMIZATION STUDY USING ONE DESIGN VARIABLE

Optimizer code	Weight, lb	Area, in.^{2}	Number of active constraints		
			Stress	Displacement	Frequency
SUMT (ref. 16)	386.613	1.116	0	0	1
IMSL (ref.13)	386.695	1.116	0	0	1
SQP (ref. 15)	386.710	1.116	0	0	1
SLP (ref. 14)	383.781	1.107	0	0	1

truss must be checked for buckling of individual members independently. The buckling is calculated from an interactive equation that considers both bending moments and axial force simultaneously (ref. 17). The buckling characteristic of members is shown in table VIII; the function F must be less than 1.0 for the

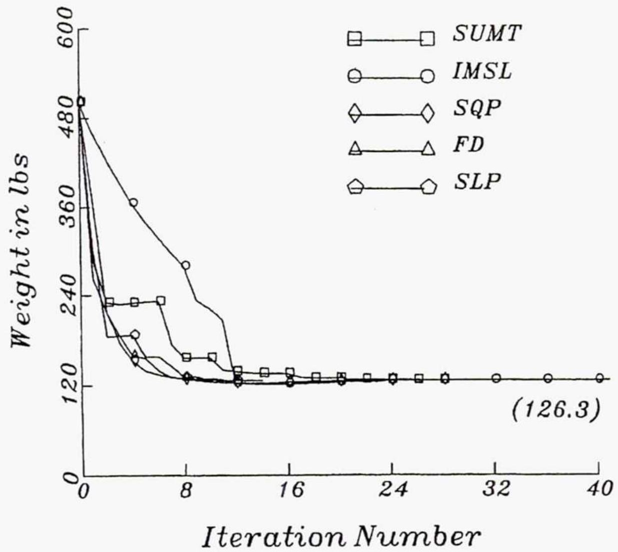


Figure 17. — Design optimization of short spacer truss with independent design variables.

TABLE VII. — OPTIMIZATION STUDY USING INDEPENDENT DESIGN VARIABLES

Optimizer code	Weight, lb	Number of active constraints		
		Stress	Displacement	Frequency
SUMT (ref. 16)	126.279	7	0	1
IMSL (ref.13)	126.194	7	0	1
SQP (ref. 15)	126.190	7	0	1
SLP (ref. 14)	126.049	7	0	1
FD (ref. 12)	127.401	6	0	1

members to be safe against buckling constraints. From table VIII, we can see that the buckling constraints are not active and that the design with respect to displacement, stress, and frequency which was obtained is adequate.

TABLE VIII. — STABILITY CRITERIA FOR TRUSS MEMBERS

Member	Stability function[a], F	Remarks
1–2	-0.6370293×10^{-1}	Tensile
1–3	$.4384254\times10^{0}$	
1–5	$.1813282\times10^{-1}$	
1–6	$.1044624\times10^{0}$	
1–7	$.1840336\times10^{-1}$	
1–8	$.6206879\times10^{-1}$	
1–9	$.1268409\times10^{0}$	
1–10	$.2298853\times10^{0}$	
2–3	$.1208779\times10^{0}$	
2–4	$.1085423\times10^{0}$	
2–5	$.2826603\times10^{-1}$	
2–10	$.9098005\times10^{-1}$	
3–4	$.5948137\times10^{-1}$	
3–5	$.5929423\times10^{0}$	
3–6	$-.1669740\times10^{-1}$	Tensile
4–5	$.1399976\times10^{0}$	
4–6	$.1977950\times10^{0}$	
4–12	$-.1005768\times10^{0}$	Tensile
4–14	$.5518738\times10^{-3}$	
5–6	$.4779148\times10^{-1}$	
6–7	$.3494801\times10^{-1}$	
6–8	$.1062912\times10^{0}$	
6–14	$.7438446\times10^{-1}$	
7–8	$.3138313\times10^{0}$	
7–9	$-.2961750\times10^{-2}$	Tensile
7–14	$.5739614\times10^{-1}$	
8–9	$.2685477\times10^{0}$	
8–14	$.9698943\times10^{-1}$	
9–10	$-.1199462\times10^{0}$	Tensile
9–11	$.6790205\times10^{-2}$	
9–13	$.8160085\times10^{0}$	
9–14	$-.8954915\times10^{-2}$	Tensile
10–11	$.4409125\times10^{-1}$	
10–12	$.1267256\times10^{0}$	
10–13	$.2179054\times10^{0}$	
11–12	$.1386686\times10^{0}$	
11–13	$.8580625\times10^{0}$	
11–14	$.4681565\times10^{-1}$	
12–13	$.1490609\times10^{0}$	
12–14	$.2332613\times10^{0}$	
13–14	$.2531832\times10^{0}$	

[a]Unity represents buckling initiation.

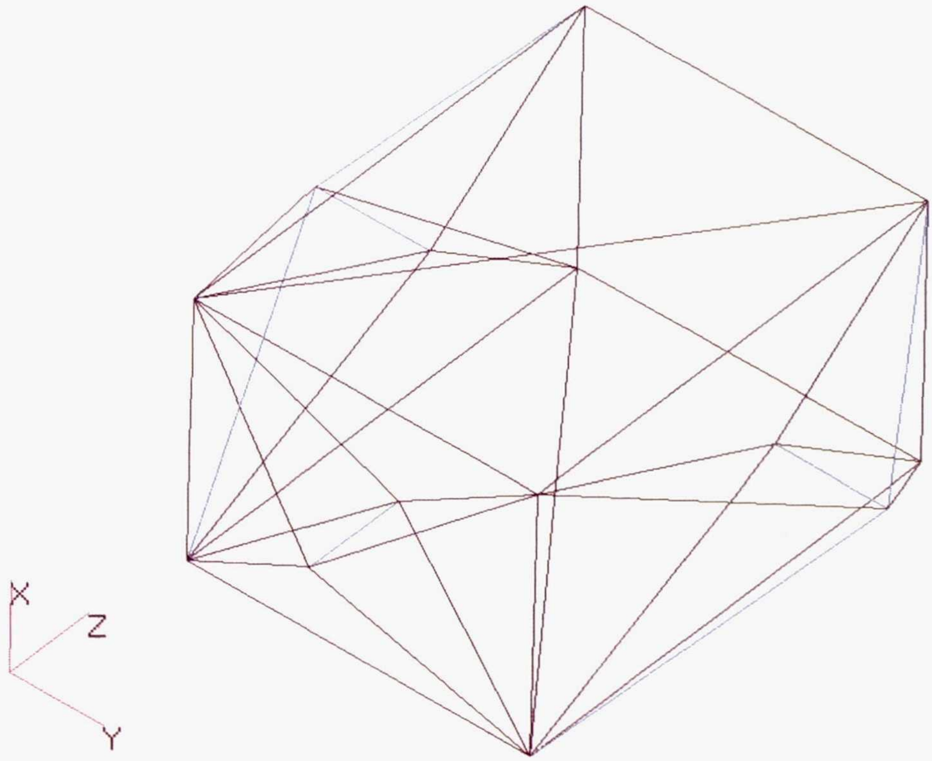


Figure 18. — Members with active stress constraints

Design Suggestions

Taking into consideration the analysis and design studies and the possibility of simplifying the joint connections (from a construction viewpoint), an alternate configuration for the short spacer truss is suggested. This new configuration can be visualized as a rectangular box with three superimposed tetrahedrons located at three faces of the box as shown in figure 19. The basic box structure provides the spacing required between the photovoltaic modules, while the three tetrahedrons provide three point supports during the launch in the STS. In the original configuration (see fig.2), the tetrahedron located in face (1-2-4-6) supports the longeron trunnion at joint 3. Since the angle between members (3-4) and (4-5) is a small acute angle of 27°, members (3-4) and (4-5) complement each other, especially in the absence of a punching load along the *y*-axis at the supporting trunnion point 3. In other words, one of these two members, that is, member (4-5), can be removed without inducing a deficiency in the design. As a preliminary recommendation, we suggest removing the following redundant members in the three tetrahedron supports:

(1) On face (1-2-4-6), connected to the longeron trunnion at joint 3 — members (1-5), (2-5), (3-5), (4-5), and (5-6)

(2) On face (1-6-14-9), connected to keel trunnion at joint 8 — members (1-7), (6-7), (9-7), (14-7), and (7-8)

(3) On face (9-10-12-14), connected to longeron trunnion at joint 13 — members (9-11), (10-11), (12-11), (14-11), and (13-11)

As already indicated, the dynamic animation (see fig.14) revealed considerable flexibility in member (1-10) because this face is not adequately braced. To overcome this deficiency, both faces parallel to the *y-z* plane should be doubly braced by providing two bracing members, one between joints 2 and 9, and the other between joints 6 and 12 (see fig. 2). The modified configuration obtained is depicted in figure 20. It has 13 joints

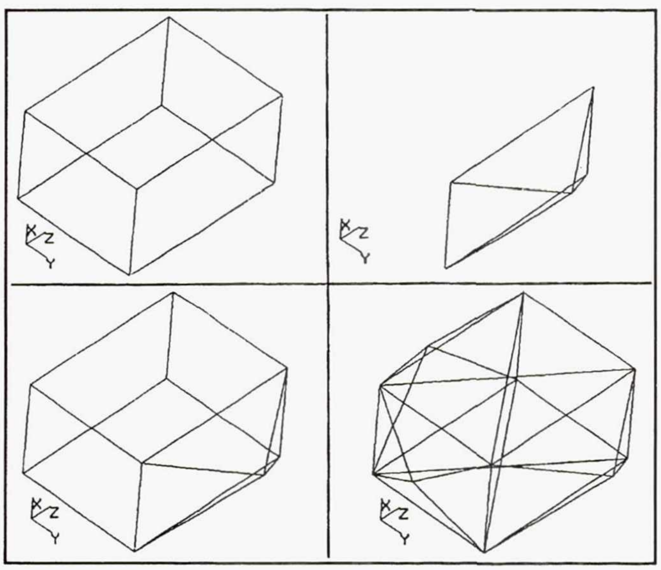


Figure 19. — Generation of modified configuration of short spacer truss.

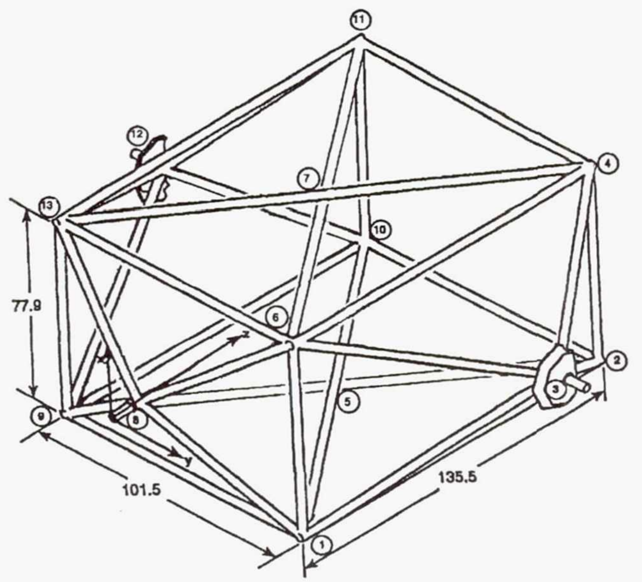


Figure 20. — Suggested (modified) configuration of short spacer truss (all dimensions are in inches).

instead of 14 joints like the original configuration; three joints have been eliminated near the supports (i.e., joints 5, 7, and 11 in fig. 2), whereas two joints have been introduced in the two planes parallel to the *y-z* plane (i.e., joints 5 and 7 in fig. 20.). The modified configuration has 32 members instead of 41, and it has fewer members and nodes, which will facilitate the fabrication of the short spacer truss.

Three different models of the short spacer truss modified configuration have been analyzed, as shown in table IX. The first two models have almost the same weight as the original configuration. Since the new configuration has fewer members than the original one, the area of its tubular members has been increased to maintain the same weight. Equal weight designs were obtained by (1) increasing the thickness from 0.2 in. to 0.25in. and keeping the diameter at 2.5 in. (model 1), and (2) increasing the diameter from 2.5 in. to 3.0 in. and maintaining the thickness at 0.2 in. (model 2). The third model had the original tubular cross section of 2.5in. diameter and 0.2 in. thickness. The maximum displacement, maximum stress, and frequency of the three different

TABLE IX. — ANALYSIS OF THE MODIFIED SHORT SPACER TRUSS CONFIGURATION

Model number	Truss weight, lb	Member diameter, in.	Member thickness, in.	Maximum displacement of truss, in.	Maximum stress of truss, psi	Frequency of truss, Hz
1	500	2.5	0.25	0.66748	15 231	10.674
2	498	3.0	.20	.44118	12 068	13.213
3	409	2.5	.20	.66469	15 379	10.649
Original	500	2.5	.20	.45633	14 791	14.283

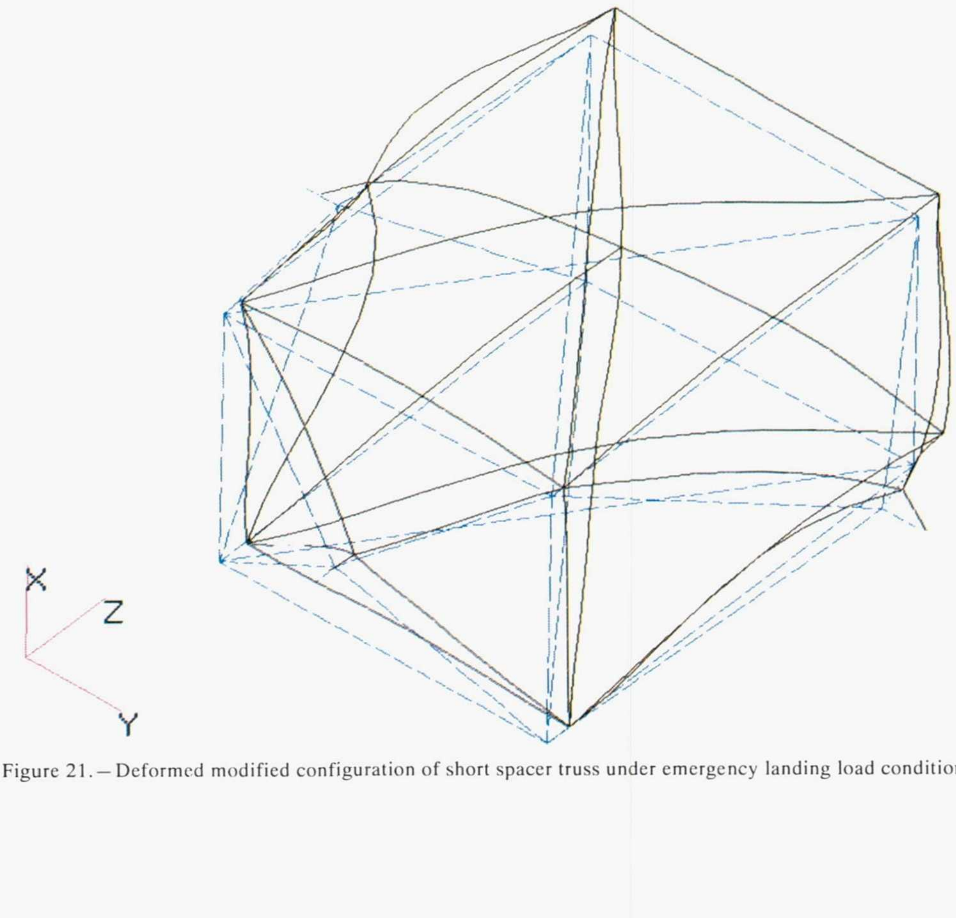


Figure 21. — Deformed modified configuration of short spacer truss under emergency landing load conditions.

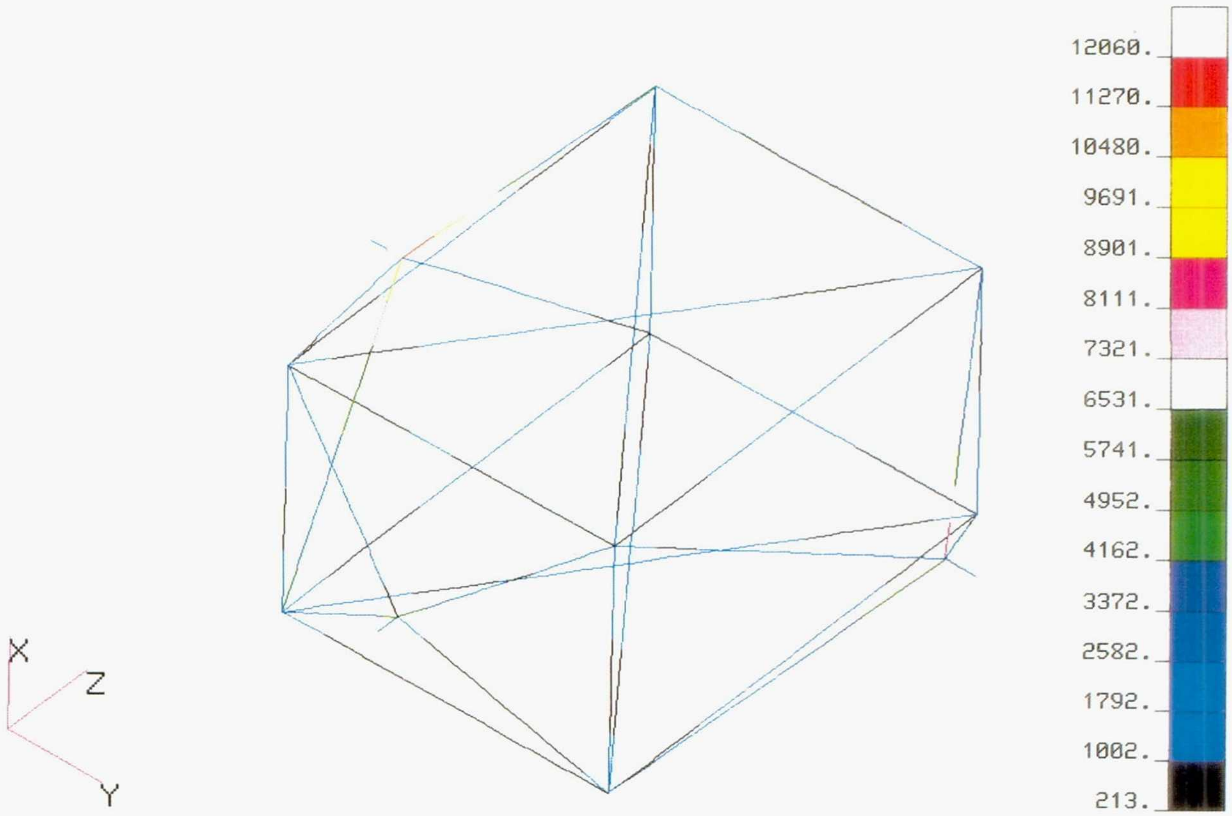


Figure 22. – Modified configuration of short spacer truss under normal stress due to emergency landing load.

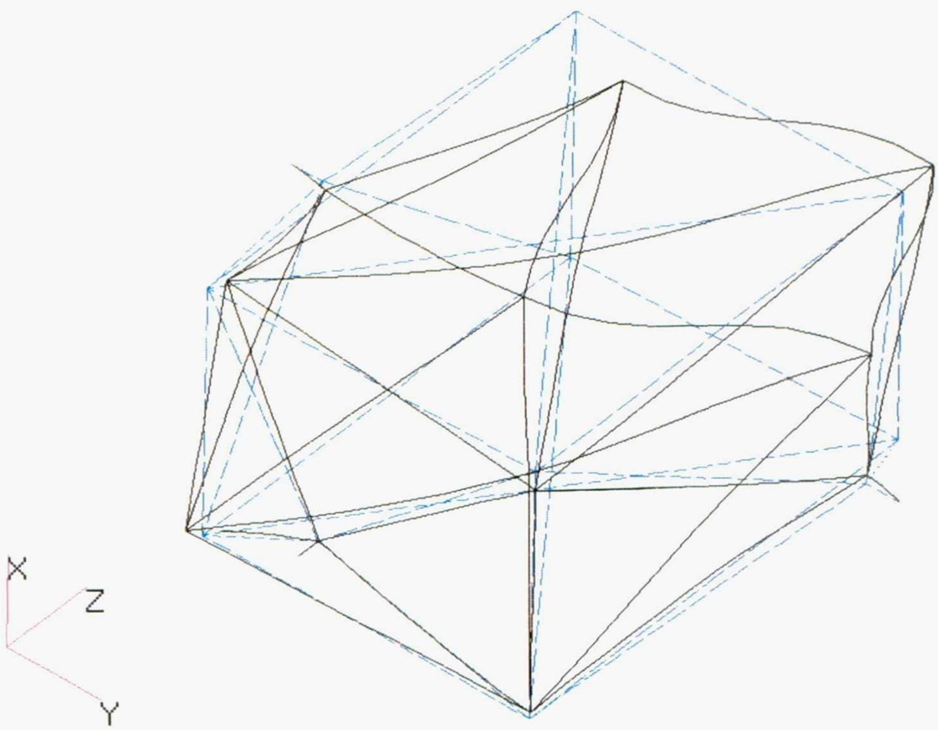


Figure 23. – First eigen mode of modified configuration of short spacer truss during launch.

models are given in table IX. As was expected, the second model (the cross section with the biggest moment of inertia) performed better than the others for displacement, stress, and frequency. When compared to the results for the original configuration, the maximum displacement, maximum stress, and fundamental frequency have been reduced by 3.3 percent, 8.5 percent, and 7.5 percent, respectively. The deformed configuration, normal stress, and fundamental mode of the second model are shown in figures 21 to 23, respectively. From the performance of the modified short spacer truss, it appears to be a viable alternative to the original truss.

Conclusions

Capabilities for analysis, dynamic simulation, and design optimization of the short spacer truss of the Space Station Freedom have been developed. These capabilities are based on the linear elastic analysis code LE_HOST, the design optimization code COMETBOARDS, and the post-processor PATRAN. The design given in this report is preliminary because the actual design specifications are not available at this time. The automated analysis and design capabilities, however, can be used to design the short spacer truss to actual specifications. The optimization process redistributed the member areas, thereby reducing the overall weight of the short spacer truss by 23 percent while keeping the same cross sectional areas for all the truss members. The preliminary results indicated that displacements are not likely to be design limitations. Frequency, on the other hand, appears to govern the design.

A modified configuration of the short spacer truss was generated; it prevents excessive deformations and simplifies the manufacturing of the truss joints. This modified configuration has been analyzed and is a feasible design which merits special consideration by the space station management.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 15, 1993

Appendix

A typical command to operate the COMETBOARDS code is as follows:

OPTIMIZE SUMT DISP OTHER STRESS DISP FREQ (OUTPUT SDF A

Next, the three data files will be prompted:

ANADAT FILE1 A
DISDAT FILE1 A
OCDAT FILE1 A

The arguments in the command represent the following:

– The first two arguments, OPTIMIZE SUMT, represent optimization with SUMT.

– The third argument, DISP, means the displacement method is the analysis tool.

– The fourth argument, OTHER, is the name for the optimization problem.

– The fifth, sixth, and seventh arguments, STRESS DISP FREQ, indicate the types of constraints considered; that is, STRESS for stress constraints, DISP for displacement, and FREQ for frequency constraints.

– The file ANLDAT FILE1 A is the analysis input data file from which the finite element analysis information is read.

– The file DISDAT FILE1 A is the design input data file from which information required to set up the optimization problem is read.

– The file OCDAT FILE1 A is the optimization input data file.

Results of the optimization problem are stored in the file OUTPUT SDF A.

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13. ABSTRACT ***(Maximum 200 words)***

The analysis, dynamic simulation, and design optimization of the short spacer truss of the Space Station Freedom are presented in this report. The short spacer truss will be positioned between the integrated equipment assembly (IEA) and another truss, called the long spacer truss, in the Space Station Freedom. During its launch in the Space Shuttle, the truss will be subjected to considerable in-span distributed inertia loads due to shuttle accelerations. The short spacer truss, therefore, has been modeled as a space frame to account for flexural response. Several parameters have been assumed, since the design specifications are in the process of development; hence the results presented should be considered preliminary. However, the automated analysis and design capabilities that have been developed can readily be used to generate an optimum design of the short spacer truss once the actual specifications have been determined. This report includes (1) static and dynamic analyses of the short spacer truss, which have been obtained with the linear elastic code LE_HOST (in these analyses, LE_HOST data files have been automated to facilitate their future use for different design specifications of the short spacer truss); (2) the dynamic animation of the short spacer truss, which has been carried out by using the results of the dynamic analysis and a post-processing feature of the modeling code PATRAN; and (3) the optimum-weight design of the spacer truss, which was obtained under prescribed stress, displacement, and frequency constraints by using the design code COMETBOARDS. Examination of the analysis and design results revealed that the design could be improved if the configuration of the short spacer truss were modified to a certain extent. A modified configuration, which may simplify fabrication, has been suggested. The performance of this configuration has been evaluated and was found to be satisfactory under both static and dynamic conditions.

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